ARMY RESEARCH LABORATORY

6.1 Research Areas in the Antenna Group

by Amir I Zaghloul

ARL-TN-0622 July 2014

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TN-0622 **July 2014**

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE *(DD-MM-YYYY)* July 2014	**2. REPORT TYPE** Final		**3. DATES COVERED (From - To)**
4. TITLE AND SUBTITLE 6.1 Research Areas in the Antenna Group			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Amir I Zaghloul			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-SER-M 2800 Powder Mill Road Adelphi, MD 20783-1197			**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TN-0622
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT Successful research in many disciplines is the result of collaborative effort between academia, industry, and Government laboratories. Such research also leads to successful transition to the field to benefit and be employed by the end user. Basic research effort at the US Army Research Laboratory (ARL) in the areas of antennas and electromagnetic falls under this general criterion, with the end user being the Soldier in the field. Selected topics are identified in this report to highlight the 6.1 research effort within the antenna group at ARL. Collaborations with academic institutions are emphasized.			
15. SUBJECT TERMS Research, antennas			

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Amir I. Zaghloul
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	14	**19b. TELEPHONE NUMBER** (*Include area code*) 301-394-0886

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

This report outlines basic research (6.1) work performed in the antenna area within the Antennas and RF Technology Integration Branch. The work is done with Army applications as the goal for transitioning this research to the field. The areas identified in this research represent topics at the cutting edge of technology in antennas and electromagnetics that is being pursued by academic, industrial, and Government organizations. In this effort, the US Army Research Laboratory (ARL) is reaching out to such organizations for productive collaboration. Individuals identified with project areas that are associated with such collaborations include the following:

- Dr W O'Keefe Coburn has participated in mentoring students from different universities in the area of simulations and modeling of antennas and electromagnetic (EM) structures.
- Dr Steven Keller has worked with University of Cincinnati on a Cooperative Agreement following a Director's Research Initiative (DRI) project. He is also working on establishing another collaboration with University of Massachusetts.
- Gregory Mitchell is working on his PhD dissertation at the George Washington University.
- Theodore Anthony is active in simulation and measurements of different designs. He has contributed to several concepts and has been a consistent supporter of student interns from Virginia Tech and George Washington University, as well as other members of the antenna team.
- Gregory Talalai is detailed at ARL from the Communications-Electronics Research, Development, and Engineering Center's (CERDEC) Space and Terrestrial Communications Directorate (S&TCD). He is completing his Masters of Engineering at the Johns Hopkins University and will join Virginia Tech for his PhD program in 2014.
- Christopher Milligan is a non-ARL Government employee with permission to perform part of his Virginia Tech PhD dissertation research at ARL.
- John A Hodge II is a guest researcher at ARL and is pursuing graduate studies at Virginia Tech, completing his Master's thesis in 2014.
- Dr Steven Weiss is the Team Leader for the Antenna Team.
- Eric Adler is the Branch Chief of the Antennas and RF Technology Integration Branch.

2. Research Areas

2.1 Novel Antenna Designs with Computational Electromagnetic Tools and In-Situ Simulations: W O'Keefe Coburn

New concepts in antenna designs are developed to improve the performance of conventional designs and meet Army requirements of low profile, small size, wideband, and enhanced gain and radiation pattern features. The new concepts are analyzed through computational EM tools that are available to the antenna group, such as FEKO and High Frequency Structure Simulator (HFSS), and are continuously updated and compared with similar tools used by other Department of Defense (DOD) organizations. Of special importance is the simulation of antenna performance in the presence of its operational environment (in-situ), such as armored vehicles, aircraft body, and field interference and scattering. Examples of novel concepts include spherical dipoles, wideband electromagnetic bandgap (EBG) surfaces, ultra-wideband, and tapered slot antennas. The realization of the antenna designs and support structures using three-dimensional (3-D) printers is an essential part of novel antenna developments.

2.2 Carbon Nanotubes (CNT) for Antenna Patches and Gas Sensors: Steven Keller

This area of research involves the design, simulation, and fabrication of durable, efficient flexible, textile-integrated, and multifunctional antennas realized from emerging nanomaterials (e.g., carbon nanotubes [CNT] and graphene). The application of bulk CNT fabrication techniques to Army antenna designs will provide extremely lightweight, durable Army antenna solutions for weight-restricted platforms and high durability antennas for conformal, textile-integrated, and/or vehicle-integrated antenna applications. Frequencies of interest range from low MHz to low THz, with the performance capabilities of the CNT bulk materials below 50 GHz being of particular interest.

Through a multi-year cooperative agreement with researchers at the University of Cincinnati, a variety of CNT thread/rope dipole, loop, and patch antennas have been simulated, fabricated, measured, and compared with standard copper antennas. Additionally, a meshed patch antenna composed of interwoven CNT threads has been developed and simulated as a concept for a multifunctional communications antenna and reactive gas sensor.

2.3 Design of Extremely Low Profile and Broadband Antennas Using Anisotropic Magnetic Metamaterials: Gregory Mitchell

Traditionally, cavity-backed apertures require an electrical height on the order of $\lambda/4$. This results in a large profile at ultrahigh frequency (UHF), because λ becomes very large. By loading the cavity with high index material, the size of λ is reduced, thereby reducing the height of the antenna's profile. Of particular interest are high index metaferrites that exhibit low loss in the UHF band.

Initial efforts included the verification of anisotropic material models using effective metamaterial media and the constituent boundary conditions. A prototype antenna loaded with such anisotropic material was fabricated and measurements were compared to those of a Computer Simulation Technology (CST) simulation incorporating the metamaterial models. These models generated very good agreement with measured results.

Current efforts include the development of a low profile and electrically small wideband antenna with –10 dB match from 300–3000 MHz. The dimensions of the antenna are to be 3 in x 3 in x 3.5 inches in height. The frequency requirements have led to an initial investigation of a spiral antenna where initial results show a 700–4000 MHz and –10 dB bandwidth for a 4.5 in x 4.5 in x 0.5 in antenna loaded with a high index dielectric. Incorporation of anisotropic magnetic materials will take advantage of the extremely high index of refraction in the transverse plane while increasing the ratio of μ/ε is expected to provide enhancements in bandwidth.

A parallel effort into the investigation of the properties of anisotropic magnetic metamaterials has led to the design of an extremely low profile cavity-backed antenna. This antenna provides a positive realized gain from 205–520 MHz, while achieving a cavity depth of 0.055 λ at 200 MHz. This is over a 70% reduction from a $\lambda/4$ cavity-backed antenna with no material loading. Suppression of higher-order modes within the loaded cavity is achieved via an anisotropic resonance condition, which leads to a novel cavity shape allowing for a 3:1 voltage standing wave ratio (VSWR) over 67% of the band. A material case study shows that the best wideband performance is achieved at the lowest frequency when a high ratio of μ/ε is used.

2.4 Electromagnetic Design and Analysis of Structures to Enhance Antenna Performance: Theodore Anthony

This general multi-faceted research investigates the realizable enhancements that intelligently structured designs around and inside antennas improve the performance of antennas on Army platforms. The structures include metamaterial inserts, oriented CNTs, ferrites, and metals. Theoretical circuit models (two-dimensional [2-D]) of desired EM responses will be developed for quick approximations. The desired closed system responses can be determined from the conversion of the simulated S-parameters to the structure’s constitutive parameters. The circuit models can then be transformed into various 3-D EM structures and infinite 2-D planar array, trying to meet the same circuit model goals. The acceptable 3-D structures are then placed around and inside the antenna in a HFSS simulation to make use of the intelligent design.

Examples include a two-arm spiral antenna that has been enhanced without the need for a balun, to have greater than a 25:1 broadband input impedance of approximately 50 ohms instead of a typical 180 ohms. A dipole antenna has been enhanced to radiate at least 2 dB greater than a typical dipole by forming a narrow azimuth beam, instead of the typical 360° azimuth beam.

2.5 Development of Theoretical Formulation and Analytical Tools for Random Metamaterials: Greg Talalai

The analysis of metamaterial structures can be achieved (arguably) most easily through examination of S-parameters, or reflection and transmission data for plane wave incidence. However, this method does not lend itself to an understanding of the underlying physics that lead to particular constitutive parameters. Alternative formulations that begin with a variation of the classic quasi-static Lorentz theory incorporate the basic physics of interaction between elements into a numerical solution of a single unit cell. This method has the potential to facilitate understanding of the material's operation, as the physical concepts are then embedded in the analysis.

Recently published literature has demonstrated that the results produced by such methods compare well with those produced by both the S-parameter extraction method and the well known mixing formulas. A similar cross examination of all of these methods is expected to lead to new ideas and concepts that may be applicable to new work involving randomly arranged metamaterials, for which reliable results have remained elusive. Intuitively, however, it is suspected that random metamaterials could have more broadband parameters, which would be of interest for typical Army applications. The expected end result of this research is analytical models that can be applied to understand the constitutive parameters of both uniformly periodic and randomly arranged metamaterials.

2.6 Active Electromagnetic Components for Control of Metamaterials and Passive Elements: Christopher Milligan

This research focuses on using active DC-powered circuitry to manipulate wave behavior within passive EM structures. Active electronic circuits can synthesize impedance functions that are not possible with passive elements, including responses are non-Foster (negative frequency derivative of reactance), nonlinear functions of frequency, and nonlinear functions of field strength. Advances in high frequency semiconductor technology now make it possible to synthesize active circuit loads at frequencies of interest to the DOD. Combining these novel impedance functions with passive electromagnetic devices to create new and different functionality has not been explored *very much* by researchers yet.

Active circuit loads exhibiting novel impedance functions have the potential to enable an entirely new class of interesting radio frequency devices. This research will focus on specific devices of interest to the DOD, namely, patch antennas, parasitic arrays, leaky wave antennas, and artificial magnetic conducting ground planes. This research will seek to address the many challenges associated with incorporating active circuits into passive devices, including stability, noise, linearity/distortion, power handling, and bias circuit design.

2.7 Characterization of Periodic and Random Metamaterials for Coherent Reflection and Frequency Selective Transmission: John A Hodge II

Researchers have readily demonstrated that artificial composite media can be engineered to exhibit exotic properties, including negative refractive index, by exploiting features in arrays of sub-wavelength unit cells. While most studies have focused on perfecting the microscopic unit cell in periodic structures, our research seeks to exploit greater bandwidth and greater isotropic properties through assembling non-periodic and randomized metamaterial structures. This emphasis on greater bandwidth and isotropic response aims at making metamaterials more suitable for practical engineering applications in the X, Ku, and Ka bands. We also seek to gain a greater understanding of the effects of disorder and non-periodicity on conventional metamaterial structures. From HFSS simulations of randomized metamaterials, a previously unreported bandpass filter effect has been observed, which can be used to engineer frequency selective surfaces (FSS).

In addition, this research introduces and explores a novel antenna-enhancing structure consisting of capacitively loaded loop (CLL) metamaterial elements placed radially around a standard dipole antenna at an electrically small distance. As a result of this novel arrangement, the dipole antenna is easily transformed into a directive mechanically scanned antenna with high realized gain. The desired directivity and gain can be tuned based on the number of radial CLL fins placed around the dipole. Interactions between the antenna and metamaterial elements result in significant enhancement of the maximum radiated field amplitude and front-to-back ratio. The structures that have been analyzed are modeled using full-wave simulation and one is experimentally verified as a proof-of-concept.

The interaction of waves transmitted by the antenna with the CLL fins is of particular interest. Current work seeks to investigate the precise mechanisms for transmission and reflection of the fin structures based on orientation and also investigates the limit in which increasing the number of radial CLL fins will no longer increase directivity of the transmitted beam. The goal of the current work is to develop a consistent theory in terms of physics that will tie together and explain the observed electromagnetic effects of periodic and single cell CLLs, random arrays of CLLs, and the CLL enhanced dipole antenna.

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3. Other Research Areas

Other areas of research within the antenna group include the following:

- *Wideband EBG surfaces*: This includes development of progressive and stacked EBG structures that can be used to reduce the profile of planar antennas of interest to Army, such as spiral antennas, UWB printed antennas, sinuous antenna, and bow-tie antenna. Circuit models, transmission line models, and full-wave analytical models are pursued.

- *Spherical dipoles*: The theory of surface-filling ropes for maximum length over a sphere is being exploited to realize the longest dipoles within a certain volume. Simulations and prototype fabrication resulted in a small antenna with performance comparable to long whip antenna. The concept has a promise for multiple- and wide-band antennas with proper layout of the dipole line over the sphere with the right line-to-gap width. Impedance matching is an essential part of the design. This work will have an impact of reducing the visibility of the whip antenna and other vehicle-mounted Army antennas.

- *Graphene-embedded polymer material for high permeability surfaces*: Use of patterned grapheme embedded in polymer material will be investigated to produce high-permeability surfaces that act as support/substrate structures for low profile antennas. This work requires collaboration with chemistry experts and will involve modeling and numerical tool development for graphene-based structures.

- *Beamforming techniques*: Distributed beamforming and cognitive beamforming are two related concepts in beam steering of arrays that include a number of apertures that are situated in extended areas in an ad-hoc fashion. An algorithm can be developed to set the beamforming parameters based on the locations of the distributed apertures and the encompassing environment. The algorithm may be based on a spatial cognitive process for the location determination and a frequency cognitive process for spectrum management purposes.

All areas listed above make use of the continuously developed simulation and measurement tools and expertise available within the Branch.

4. Conclusion

Areas of antenna research of direct applications to Army needs were identified in this report. Improving the antenna performance and reducing its size, weight, and visibility help the Soldier in the field. This was demonstrated in the different examples of advanced research that used new materials and new configurations to achieve these goals. Collaborations with academic institutions were emphasized.

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
3-D	three-dimensional
ARL	US Army Research Laboratory
CERDEC	Communications-Electronics Research, Development, and Engineering Center
CLL	capacitively loaded loop
CNT	carbon nanotube
CST	Computer Simulation Technology
DOD	Department of Defense
DRI	Director's Research Initiative
EBG	electromagnetic bandgap
EM	electromagnetic
FSS	frequency selective surfaces
HFSS	High Frequency Structure Simulator
S&TCD	Space and Terrestrial Communications Directorate
UHF	ultrahigh frequency
VSWR	voltage standing wave ratio

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